ASD-TDR-63-645

ELEVATED TEMPERATURE FATIGUE PROPERTIES OF D6AC HIGH STRENGTH STEEL

SIDNEY O. DAVIS

TECHNICAL DOCUMENTARY REPORT No. ASD-TDR-63-645

OCTOBER 1963

AF MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 7381, Task No. 738103

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified requesters may obtain copies of this report from the Defense Documentation Center (DDC), (formerly ASTIA), Cameron Station, Bldg. 5, 5010 Duke Street, Alexandria 4, Virginia

This report has been released to the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C., in stock quantities for sale to the general public.

Copies of this report should not be returned to the Aeronautical Systems Division unless return is required by security considerations, contractual obligations, or notice on a specific document.

200 - December 1964 - 448-21-517

FOREWORD

This report was prepared by Sidney O. Davis of the Load Bearing Materials Section, Materials Engineering Branch, Materials Application Division, AF Materials Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. This program was conducted under Project No. 7381, "Materials Applications," Task No. 738103, "Data Collection and Correlation."

This report covers work conducted from January 1960 to April 1963.

The testing was done by Monsanto Research Corporation (utilizing Materials Application Division, AF Materials Laboratory in-house test facilities) under Contract No. AF 33(616)-8483 and Lessells and Associates, Inc. under Contract No. AF 33(616)-6946.

ABSTRACT

A program was conducted to obtain complete stress versus number of cycles (S-N) curves for D6AC steel heat treated to an ultimate strength of 270 KSI.

Tension-tension fatigue tests were conducted on notched and unnotched specimens at 75°, 450°, and 550°F for stress ratios of 1 and ∞

Tensile and stress rupture data was obtained in conjunction with the fatigue data.

This technical documentary report has been reviewed and is approved.

W. P. Conrardy

W. P. CONRARDY
Chief, Materials Engineering Branch
Materials Application Division
AF Materials Laboratory

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

The performance requirements for modern airborne systems have resulted in needs for higher strength materials. One such material is D6AC, a low alloy high strength steel, developed by Ladish for hot work die applications.

Two current applications of this material are rocket motor cases in the 1st stage Minuteman and 1st and 2nd stage Pershing missiles. These applications require a vacuum melt grade similar to that tested in this program. The D6AC used here was heat treated to an ultimate strength of 270 KSI. For a complete discussion of the mechanical properties of D6AC see reference 1.

This report supplements the D6AC high cycle tension-tension fatigue data reported by Lessells and Associates, Inc. in ASD-TDR-62-480, "Fatigue and Dynamic Creep of High-Strength Steels."

The purpose of this program was to generate low cycle tension-tension fatigue data on D6AC so complete S-N diagrams would be available. The specimens used for this continuing effort were supplied by Lessells and thus were identical to those of the initial contract.

Lessells' data is repeated in this report, where appropriate, for the sake of uniformity in presentation. No distinction is made in the text as to origin of data. However, the low cycle fatigue ($<10^4$ cycles) data was obtained in the Load Bearing Materials Section, Materials Application Division, ASD; all other information and data contained herein originated from Lessells.

The net result of this combined effort between ASD and Lessells is comprehensive S-N fatigue diagrams for D6AC at room temperature, 450°F, and 550°F with test ratios of $A = \infty$ and $A = 1$* on notched and unnotched specimens.

SPECIMENS

Table 1 gives the composition, heat treatment, and average room temperature unnotched tensile information for the material tested. Complete tensile data is shown in table 8 of the Appendix.

A photomicrograph of the material is shown in figure 1.

Specimens were machined from one-half inch bar in the annealed condition to the configuration shown in figures 2 and 3. They were rough machined to approximately 0.030 inch oversize and heat treated. Following heat treatment, the specimens were ground to finish dimensions using a series of grinding passes of decreasing depth. Unnotched test sections were longitudinally machine-polished with a 600-grit belt. Notch root radii were polished by means of a rotating abrasive thread. Specimens were notched to a theoretical stress concentration of 3.0.

---

* $A = \dfrac{\text{Alternating stress}}{\text{Mean stress}}$

Manuscript released by the author 27 June 1963 for publication as an ASD Technical Documentary Report.

TABLE 1

MATERIAL INFORMATION

Material	Supplier	Heat No.	C	Mn	Si	S	P	Cr	V	Ni	Mo	Fe
D6AC	Crucible	S9706	0.44	0.64	0.24	0.01	0.006	1.03	0.06	0.50	1.01	Bal

Heat Treatment: 1500°F - 15 min. (slightly oxidizing)

Oil Quench

500°F - 2 hours

Tensile Data (Avg):

Material	0.2% Y. S.	U. T. S.	% Elongation	% Reduction in Area (R. A.)
D6AC	237,000 psi	270,000 psi	5.3	38.3

Figure 1. Photomicrograph of D6AC - Vilella's Reagent, 1000X

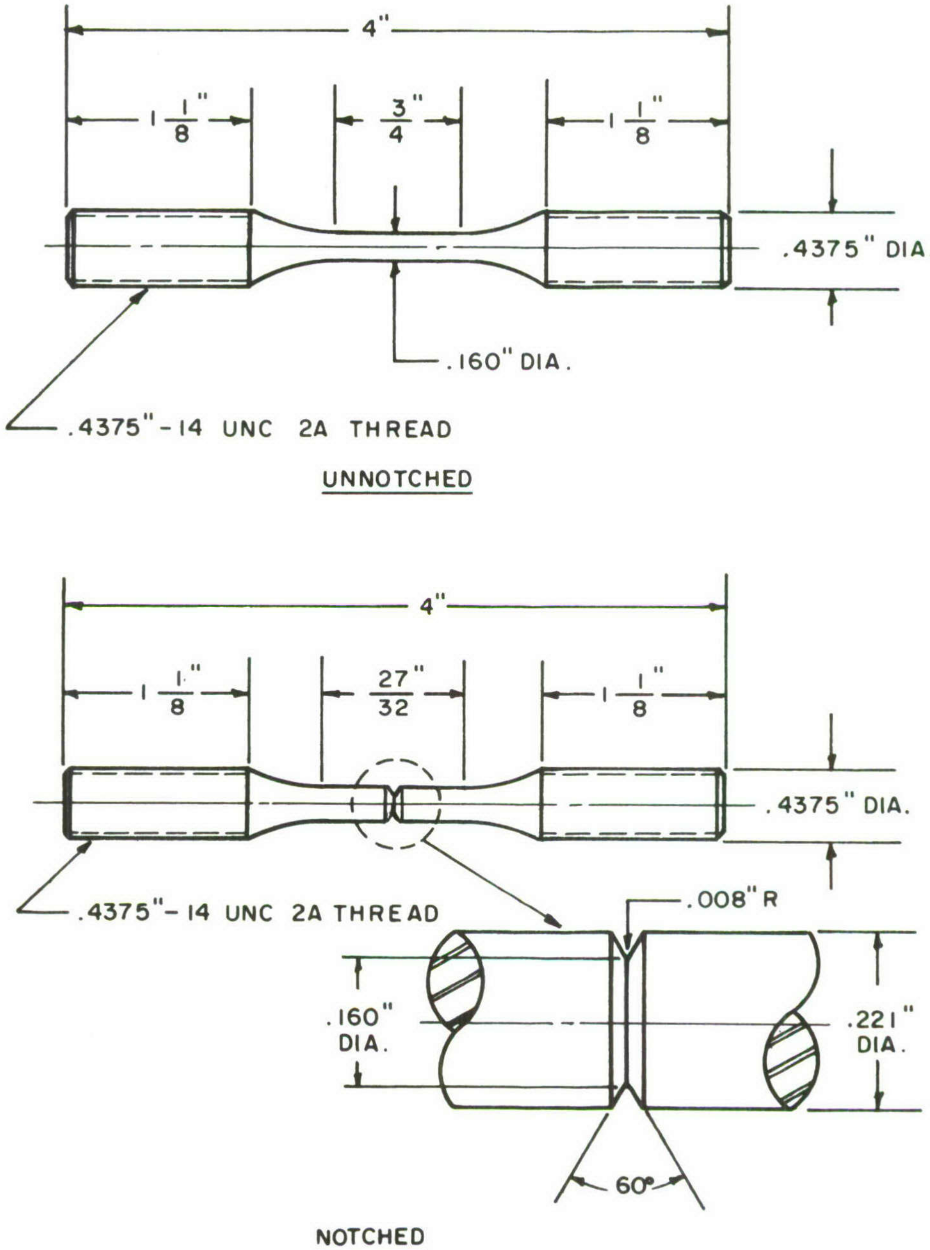

Figure 2. Fatigue Specimens

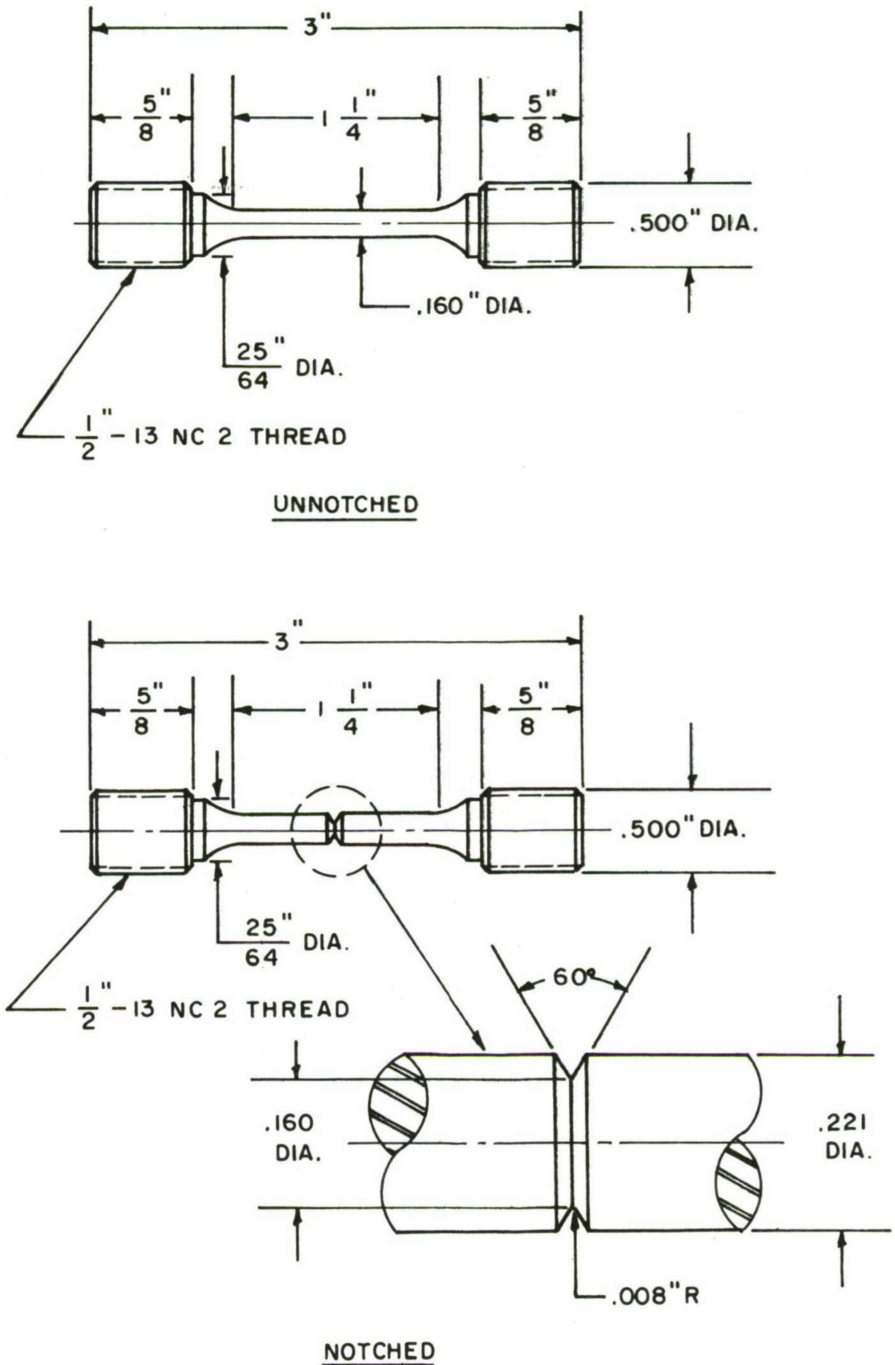

Figure 3. Tensile and Stress Rupture Specimens

TEST EQUIPMENT

High cycle fatigue tests were conducted on a Type PVQ Schenck vertical fatigue machine. Low cycle tests were run on a Wiedemann-Baldwin Model FGT tensile machine. Cycle rates of approximately 3100 cpm and 8-10 cpm were used.

Temperature was monitored and controlled to $\pm 3^{\circ}F$ over the $\frac{3}{4}$ inch specimen gage length.

For a discussion of the high cycle fatigue test equipment see reference 2.

Figure 4 shows the setup used to obtain the low cycle fatigue data. The tension-compression grips shown are commercially available. A tensile preload was used when loading the specimen to insure axial alignment.

The tensile and stress rupture tests were conducted by New England Materials Laboratory, Medford, Mass.

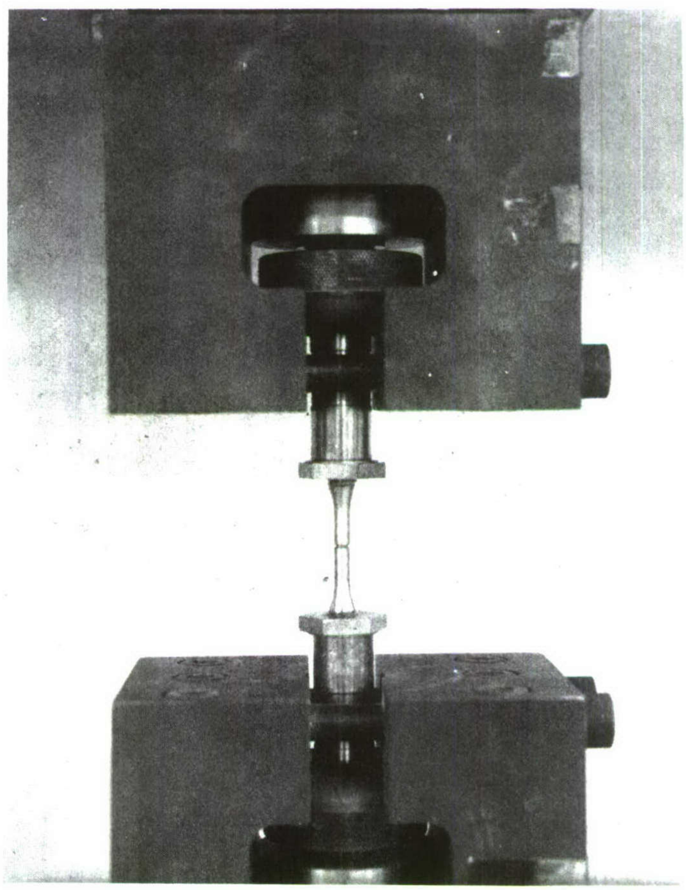

Figure 4. Mounting of Low Cycle Fatigue Specimens

TEST SCHEDULE

Table 2 presents an outline of the test program.

TABLE 2

TEST CONDITIONS

MATERIAL	NOTCH	STRESS RATIO (A)	TEMPERATURE (°F)	TOTAL CONDITIONS	SPECIMENS/ CONDITION	TOTAL SPECIMENS
TENSILE TESTS						
D6AC	UN, N	0	75,450,550	6	3	18
FATIGUE TESTS						
1. HIGH CYCLE						
D6AC	UN, N	1, ∞	75, 450, 550	12	8	96
2. LOW CYCLE						
D6AC	UN	1, ∞	75, 450, 550	6	7	42
D6AC	N	1, ∞	75, 550	4	8	32
STRESS RUPTURE TESTS						
D6AC	UN, N	0	450, 550	4	5	20

Elevated temperature stress rupture loads were selected to allow interpolation to a rupture life of 55 hours. This time corresponded to that required for the accumulation of 10 million cycles by the Schenck fatigue machine. By convention, the resultant stress values are plotted on modified Goodman diagrams as $A = 0$ for the corresponding elevated test temperatures.

RESULTS

All detailed test data is tabulated in the Appendix. It should be noted that no low cycle fatigue tests were run on notched specimens at 450°F due to an insufficient quantity of specimens. Therefore, only Lessells' high cycle fatigue data is plotted for this condition.

Modified Goodman diagrams are presented in figure 11 of the Appendix. Tabulated stress rupture data is in table 7.

DISCUSSION

Fatigue Characteristics

The S-N diagrams and corresponding tabulated data are shown in figures 5 through 10 and tables 3, 4, 5 respectively.

A good correlation between high and low cycle results is evident considering the inherent scatter of fatigue results.

The notched and unnotched curves cross in the range of 10-100 cycles, but no explanation of this can be offered.

Table 6 of the Appendix lists the values of the notch-sensitivity index (q) for D6AC. In this case q is based on a biaxial stress factor ($K_{T'}$) of 2.7 where the uniaxial factor (K_T) of the notches is 3.0. The notch-fatigue factor (K_f) which is the ratio of the unnotched to notched fatigue limit is also tabulated.

Examination of the failed surfaces of the high cycle specimens showed the failures to have initiated both at the surface and internally. Although poor axial alignment, a potential problem with threaded specimens, can cause failure initiation at the surface, localized surface conditions also can be a cause.

Low cycle fatigue specimen examination indicated ductile failures on the unnotched specimens with fracture surfaces appearing gray and fibrous. In most cases the fracture surface was characterized by a cup-and-cone or full-shear failure. Therefore, considerable evidence indicated that the failure initiated internally, probably due to voids forming in the specimen in the region of triaxial stress. In both high and low cycle tests the percent of shear failure increased with test temperature.

The failure surface appearance of the notched low cycle specimens indicated some plastic flow around the root of the notch; however no elongation measurements were attempted.

Examination of the modified Goodman diagrams shows that mean stress and temperature cause a decrease in the allowable alternating stress. The test points are joined by straight lines since a limited number of stress ratios were used.

Stress Rupture Characteristics

The stress rupture curves of D6AC, as shown in figure 12 of the Appendix, show the stress versus time function to be very flat. The interpolated value of stress for a life of 55 hours (10^7 cycles on the Schenck machine) was obtained from these plots.

"Examination of the failed surface of the stress rupture specimens revealed no consistent pattern," (ref 2).

Figure 13 of the Appendix shows the elongation at fracture for the failed D6AC stress rupture specimens.

CONCLUSIONS

1. Extensive S-N diagrams were obtained for D6AC high strength steel. Additional information includes tensile and stress rupture properties.

2. The ratio of fatigue strength (at 10 million cycles) to ultimate tensile strength ranged from .28 - .33 for $A = \infty$ on the unnotched specimens. For $A = 1$ the fatigue ratio was .49 - .54.

3. The fracture surfaces of both the low and high cycle fatigue unnotched specimens indicated a ductile shear failure with the percent of shear increasing with increasing test temperature.

4. The fatigue information, compiled from two different sources using the same specimens, showed good correlation between high and low cycle results.

REFERENCES

1. Air Weapons Materials Application Handbook - Metals and Alloys, AFSC Supplement I, August 1962.

2. Lessells and Associates, Inc., Fatigue and Dynamic Creep of High-Strength Steels, ASD-TDR-62-480, August 1962.

3. Dieter, G. E., Mechanical Metallurgy, McGraw-Hill, New York, New York, 1961, p. 315.

APPENDIX

TEST DATA AND RESULTS

TABLE 3
FATIGUE TEST DATA, 75°F

NOTCH	STRESS RATIO	MAXIMUM STRESS (KSI)	CYCLES TO FAILURE
UN	1	270	1184
UN	1	263	2538
UN	1	250	4863
UN	1	225	11,208
UN	1	220	26,300
UN	1	200	39,000
UN	1	180	78,200
UN	1	170	122,300
UN	1	170	437,900
UN	1	160	183,000
UN	1	150	14,173,100*
UN	1	140	13,001,300*
N	1	300	91
N	1	270	102
N	1	250	220
N	1	200	910
N	1	178	1272
N	1	140	2490
N	1	140	7100
N	1	120	12,600
N	1	110	33,200
N	1	100	54,300
N	1	90	61,600
N	1	80	229,000
N	1	80	10,592,400*
N	1	60	13,639,400*
UN	∞	250	13
UN	∞	226	66
UN	∞	221	153
UN	∞	221	150
UN	∞	199	497
UN	∞	186	1395
UN	∞	172	7458
UN	∞	160	20,000
UN	∞	140	38,500
UN	∞	120	71,700
UN	∞	110	93,500
UN	∞	100	90,400
UN	∞	100	11,106,800*
UN	∞	100	19,538,000*
UN	∞	80	13,294,800*

* INDICATES SPECIMEN DID NOT FAIL

TABLE 3 (CONT'D)

NOTCH	STRESS RATIO	MAXIMUM STRESS (KSI)	CYCLES TO FAILURE
N	∞	300	5
N	∞	250	16
N	∞	200	68
N	∞	140	636
N	∞	100	1884
N	∞	100	7900
N	∞	80	13,000
N	∞	70	5636
N	∞	70	25,300
N	∞	65	33,000
N	∞	60	72,100
N	∞	50	1,438,000
N	∞	50	17,021,100*
N	∞	40	15,699,200*

* INDICATES SPECIMEN DID NOT FAIL

TABLE 4

FATIGUE TEST DATA, 450°F

NOTCH	STRESS RATIO	MAXIMUM STRESS (KSI)	CYCLES TO FAILURE
UN	1	263	2050
UN	1	255	3318
UN	1	225	5813
UN	1	200	41,400
UN	1	180	22,700
UN	1	170	369,300
UN	1	160	1,322,700
UN	1	150	3,163,400
UN	1	140	6,601,900
UN	1	135	6,541,700
UN	1	135	9,114,600
UN	1	135	13,050,000*
N	1	300	43**
N	1	200	4020**
N	1	100	17,506***
N	1	100	13,700
N	1	100	23,400
N	1	90	32,700
N	1	85	42,300
N	1	80	551,300
N	1	75	902,200
N	1	70	1,014,700
N	1	60	10,555,880*
UN	∞	235	74
UN	∞	225	165
UN	∞	200	511
UN	∞	180	3193
UN	∞	160	7464
UN	∞	130	46,500
UN	∞	120	160,100
UN	∞	110	517,300
UN	∞	95	1,555,400
UN	∞	90	3,719,900
UN	∞	80	13,107,300*
N	∞	300	8**
N	∞	70	19,600
N	∞	65	23,100
N	∞	60	42,100
N	∞	55	41,500
N	∞	50	55,000
N	∞	45	143,700
N	∞	40	7,615,600
N	∞	40	12,075,000*

* INDICATES SPECIMEN DID NOT FAIL
** NOT PLOTTED
*** LOW CYCLE FATIGUE VALUE

TABLE 5
FATIGUE TEST DATA, 550°F

NOTCH	STRESS RATIO	MAXIMUM STRESS (KSI)	CYCLES TO FAILURE
UN	1	245	1453
UN	1	237	1335
UN	1	230	5518
UN	1	224	4902
UN	1	200	13,100
UN	1	180	48,300
UN	1	160	618,100
UN	1	150	724,700
UN	1	150	1,599,500
UN	1	140	5,895,800
UN	1	135	13,450,000*
UN	1	130	10,125,000*
N	1	300	73
N	1	300	84
N	1	250	143
N	1	200	280
N	1	150	916
N	1	120	2438
N	1	100	13,112**
N	1	100	20,000
N	1	90	23,300
N	1	90	39,500
N	1	80	79,900
N	1	80	163,000
N	1	70	642,900
N	1	60	4,854,000
N	1	55	10,100,000*
UN	∞	234	24
UN	∞	223	100
UN	∞	208	303
UN	∞	198	186
UN	∞	198	202
UN	∞	189	534
UN	∞	163	1474
UN	∞	140	19,800
UN	∞	120	199,800
UN	∞	110	162,900
UN	∞	100	1,217,300
UN	∞	90	2,992,300
UN	∞	80	2,672,600
UN	∞	80	7,423,800
UN	∞	75	12,462,000*
N	∞	244	6
N	∞	200	28
N	∞	150	180
N	∞	100	1341
N	∞	70	13,900
N	∞	65	17,400
N	∞	60	34,800
N	∞	55	37,000
N	∞	55	59,400
N	∞	50	82,700
N	∞	45	248,800
N	∞	40	15,550,000*

* INDICATES SPECIMEN DID NOT FAIL
** LOW CYCLE FATIGUE VALUE

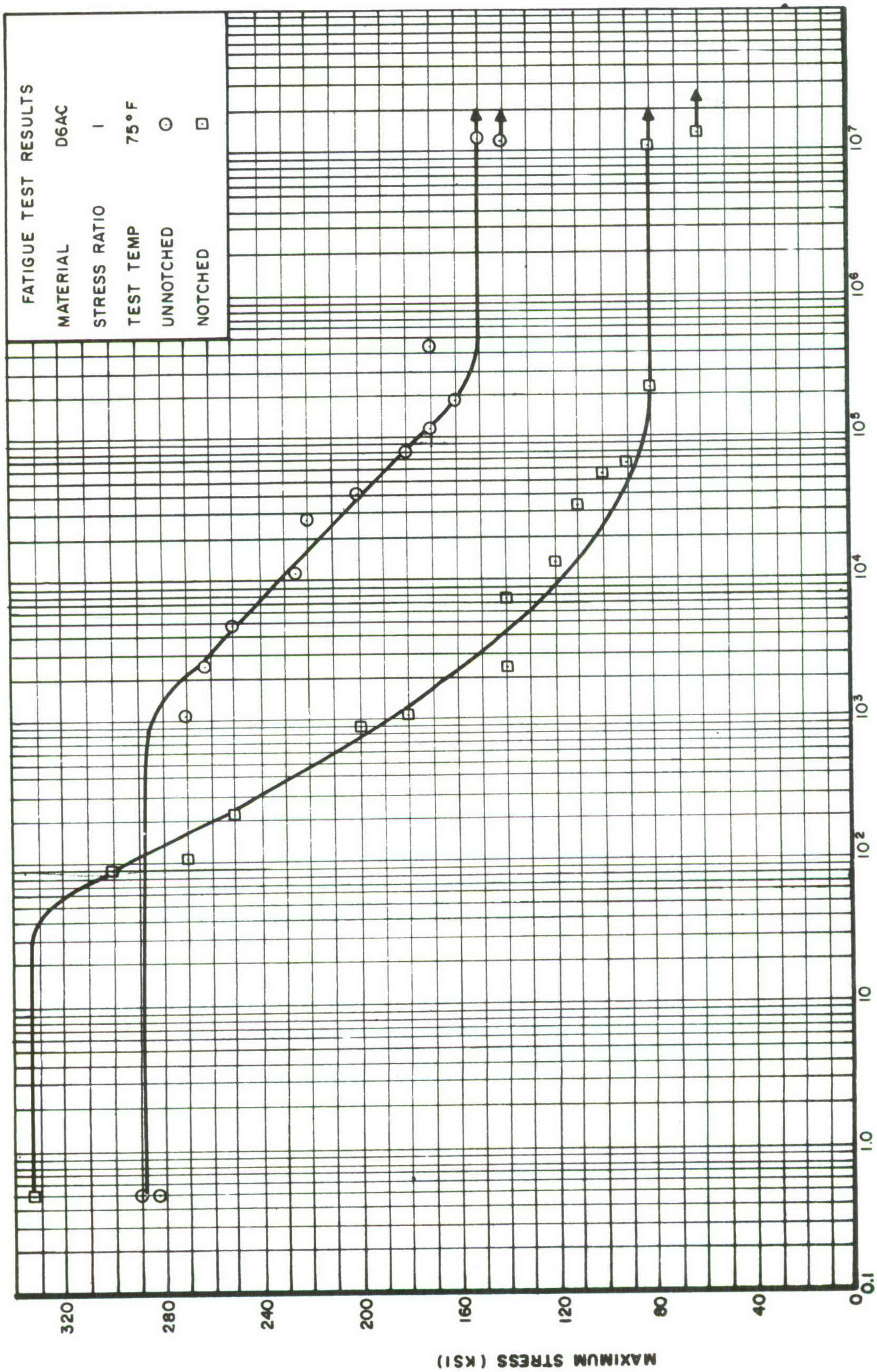

Figure 5. S-N Diagrams: D6AC, A = 1, 75°F

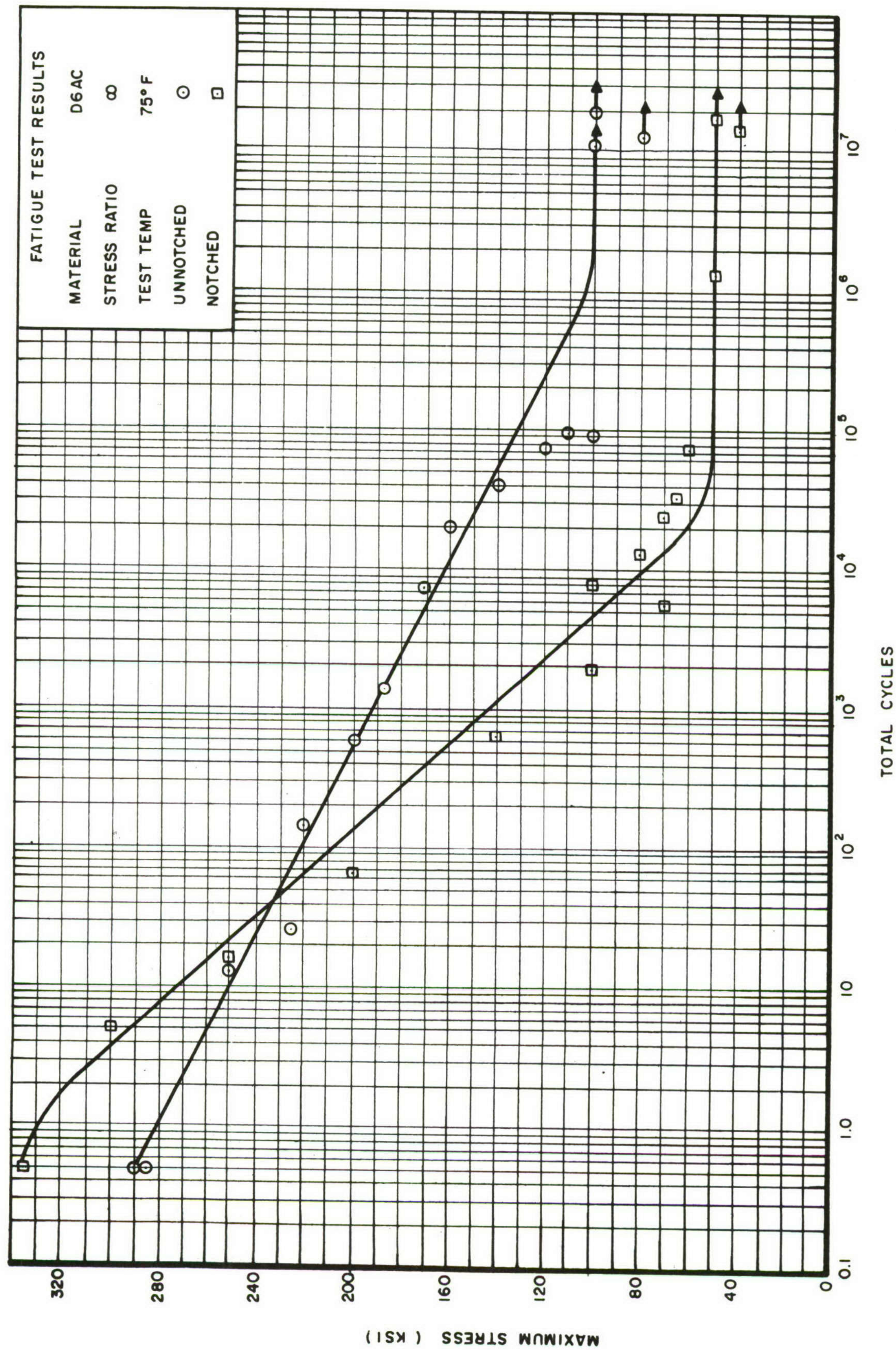

Figure 6. S-N Diagrams: D6AC, A = ∞, 75°F

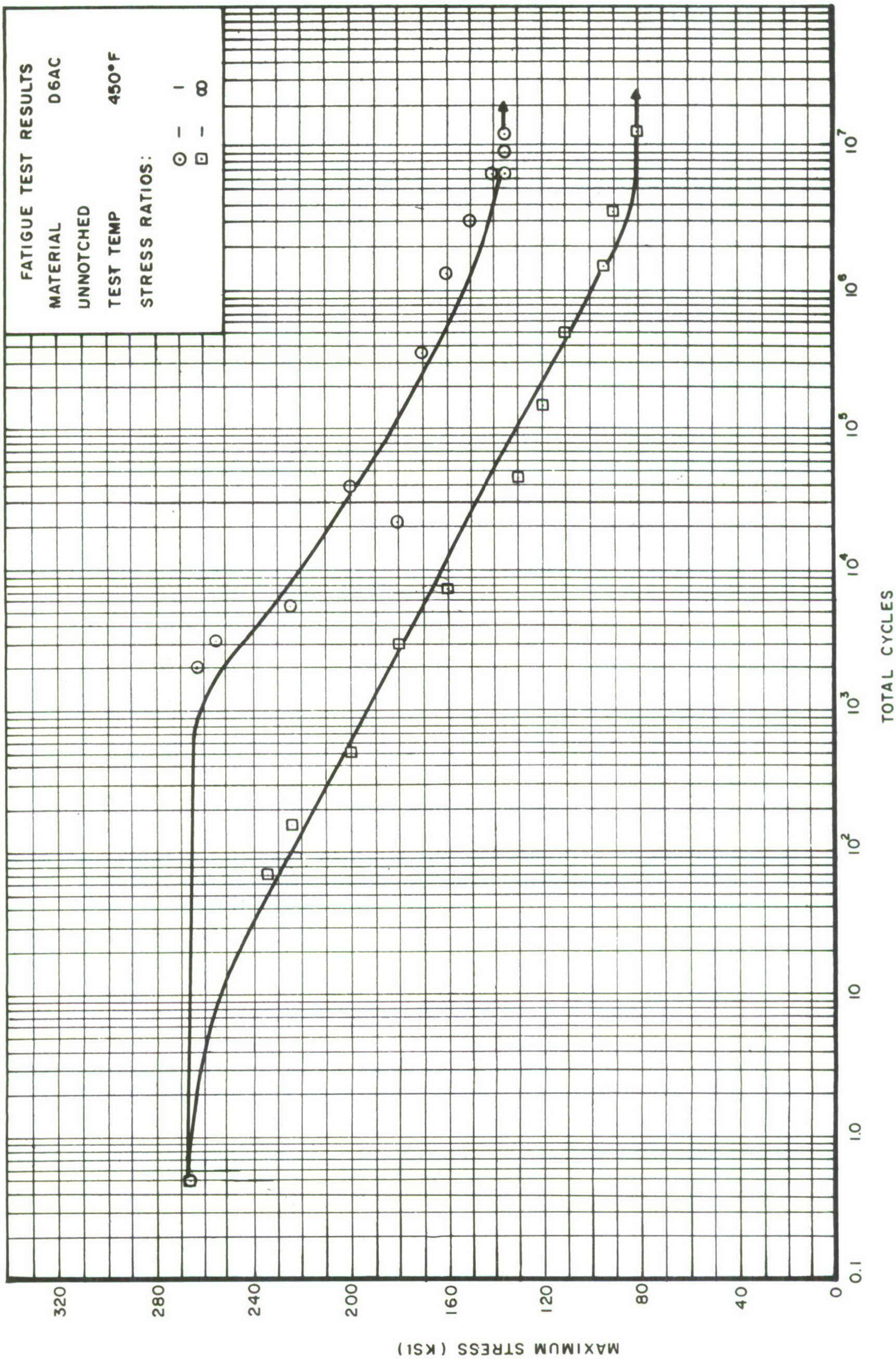

Figure 7. S-N Diagrams: D6AC, 450°F, Unnotched

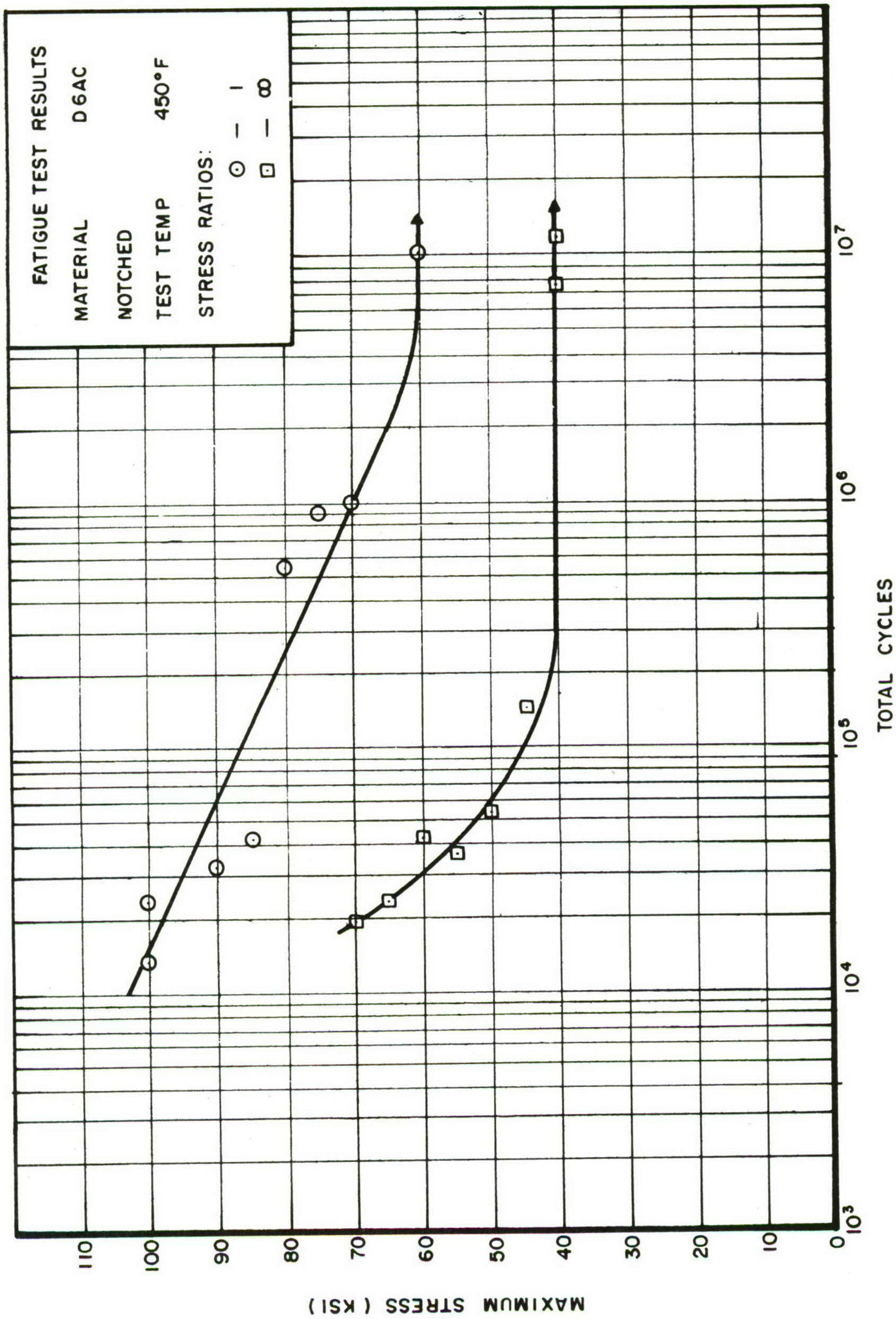

Figure 8. S-N Diagrams: D6AC, 450°F, Notched

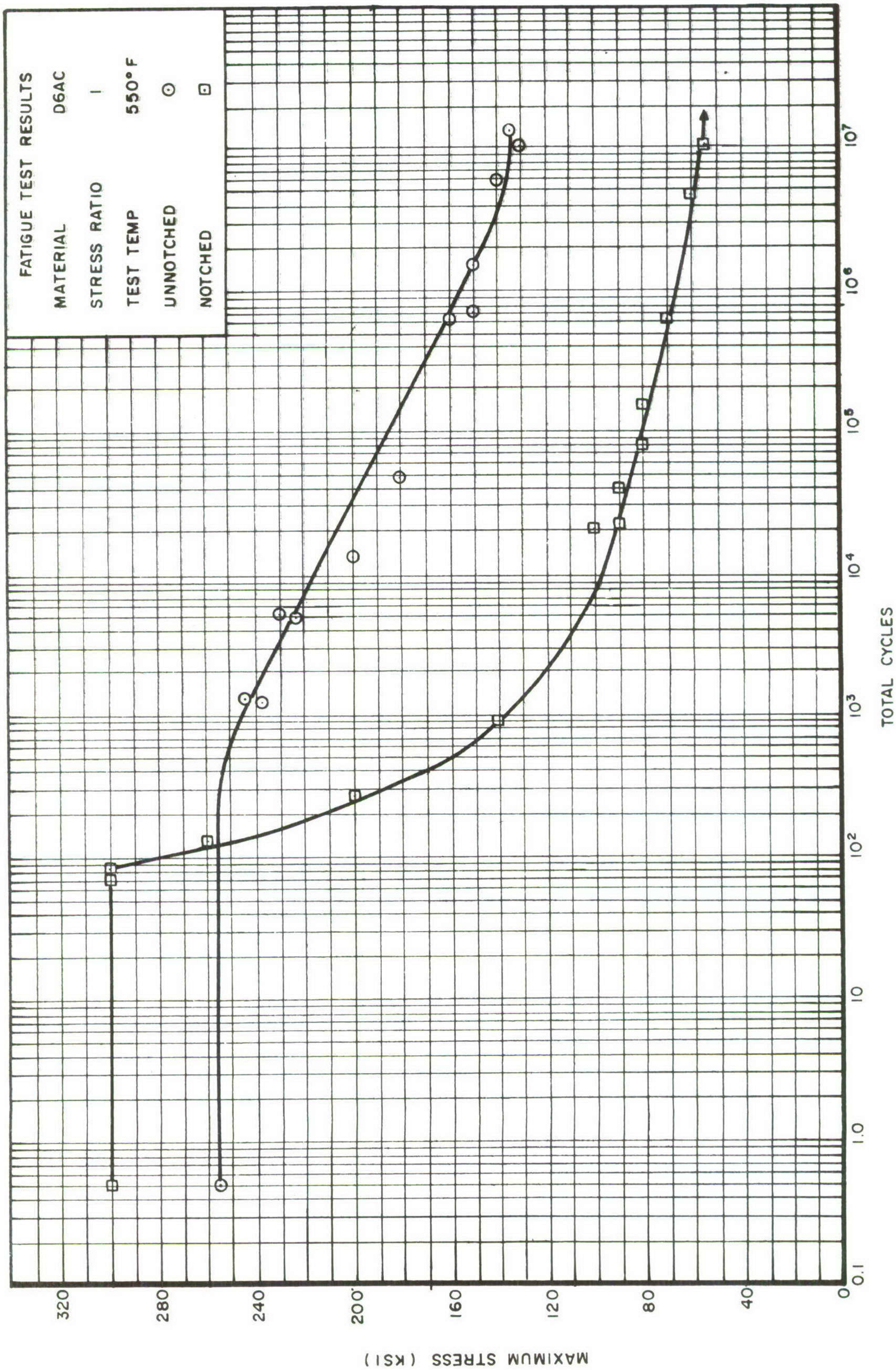

Figure 9. S-N Diagrams: D6AC, A = 1, 550°F

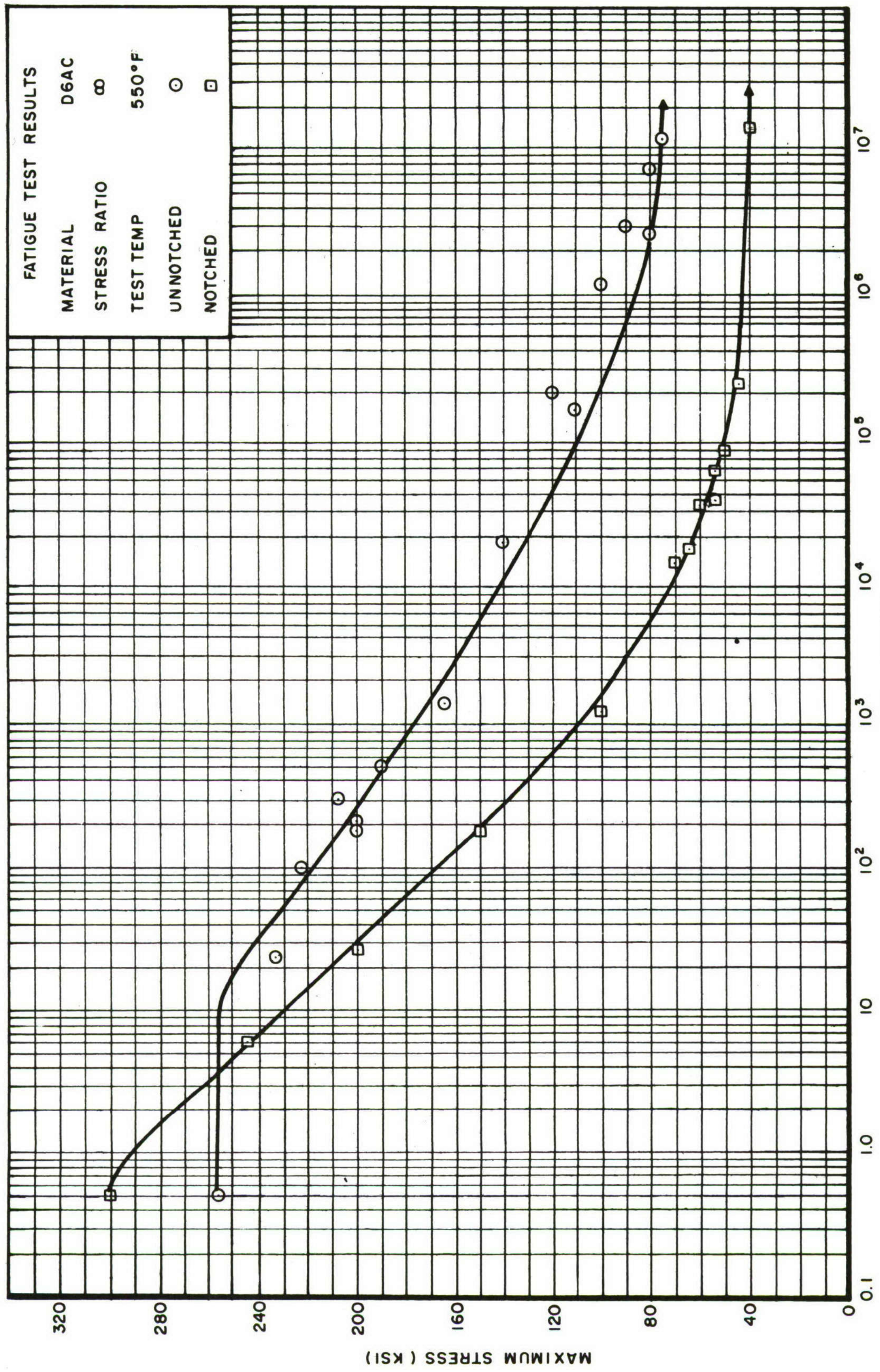

Figure 10. S-N Diagrams: D6AC, A = ∞, 550°F

TABLE 6

NOTCH SENSITIVITY

STRESS RATIO A = ∞ $\qquad q = \dfrac{K_f - 1}{K_{T'} - 1}$ (REFERENCE 3)

MATERIAL	TEST TEMPERATURE (°F)	K_f	q
D6AC	75	2.0	.59
	450	2.0	.59
	550	1.88	.52

TABLE 7

STRESS RUPTURE DATA

MATERIAL	NOTCH	TEST TEMP (°F)	STRESS PSI	% ELONGATION	% R. A.	LIFE (HOURS)
D6AC	UN	450	250,000	10.6	17.9	0.5
	UN	450	238,000	7.2	37.4	0.0083
	UN	450	233,000	8.5	33.5	97.4
	UN	450	235,000	7.6	33.4	9.4
	UN	450	234,000	DISCONTINUED AT 1063.0		
	UN	550	225,000	8.67	43.7	0.0083
	UN	550	218,000	7.05	45.7	0.5
	UN	550	205,000	6.45	28.4	69.1
	UN	550	210,000	DISCONTINUED AT 1063.0		
	UN	550	214,000	6.99	48.0	26.6
D6AC	N	450	360,500			1.0
	N	450	355,000			0.0166
	N	450	350,000			5.4
	N	450	345,000			24.7
	N	450	340,000			43.2
	N	550	306,600			44.3
	N	550	315,000			6.4
	N	550	310,000			3.6
	N	550	300,000			689.5
	N	550	308,000			30.1

TABLE 8

TENSILE TEST DATA

MATERIAL	NOTCH	TEST TEMP (°F)	0.2% Y. S. PSI	U.T.S. PSI	% ELONGATION	% R. A.
D6AC	UN	75	237,000	275,000	5.18	39.3
	UN	75	238,000	265,000	5.19	36.4
	UN	75	237,000	269,000	5.50	39.3
	UN	450	176,000	259,000	10.2	43.8
	UN	450	165,500	266,000	10.6	39.4
	UN	450	175,500	255,000	10.6	37.4
	UN	550	158,500	230,000	11.0	52.8
	UN	550	166,000	239,000	12.2	57.3
	UN	550	155,000	229,000	11.4	57.3
D6AC	N	75		330,000		
	N	75		334,000		
	N	75		349,000		
	N	450		362,000		
	N	450		383,000		
	N	450		387,000		
	N	550		372,000		
	N	550		369,000		
	N	550		358,000		

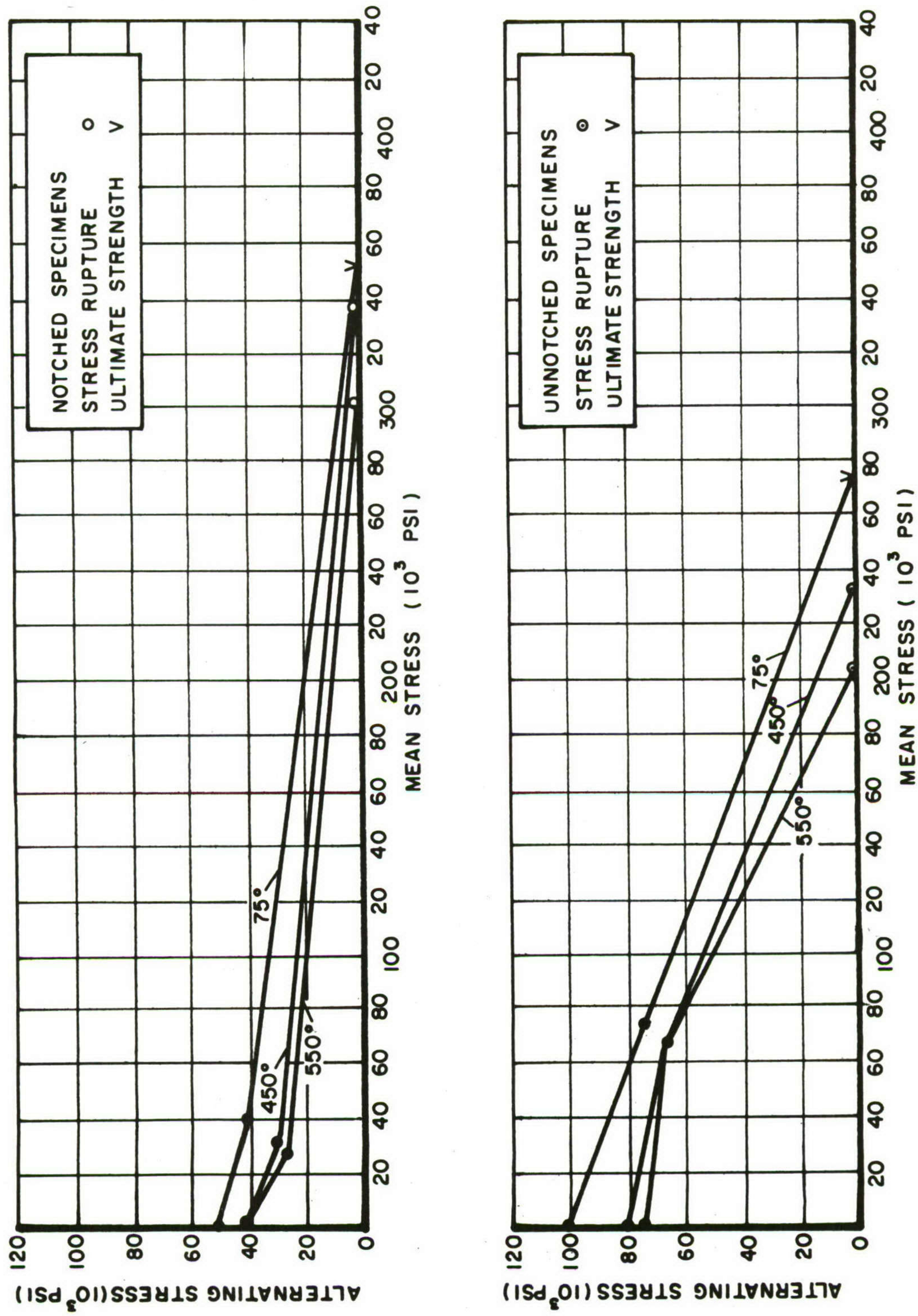

Figure 11. Modified Goodman Diagram

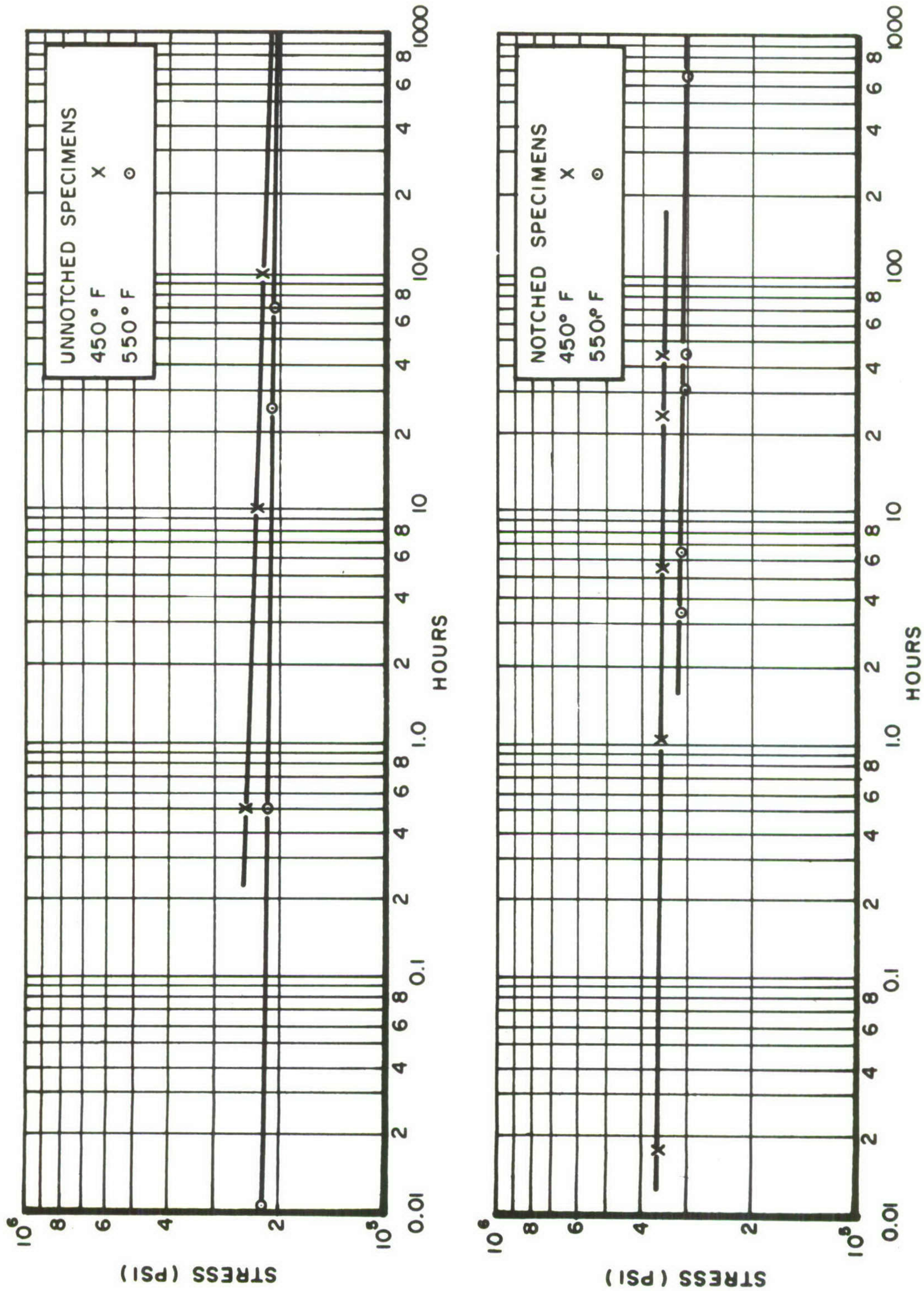

Figure 12. Stress Rupture Data

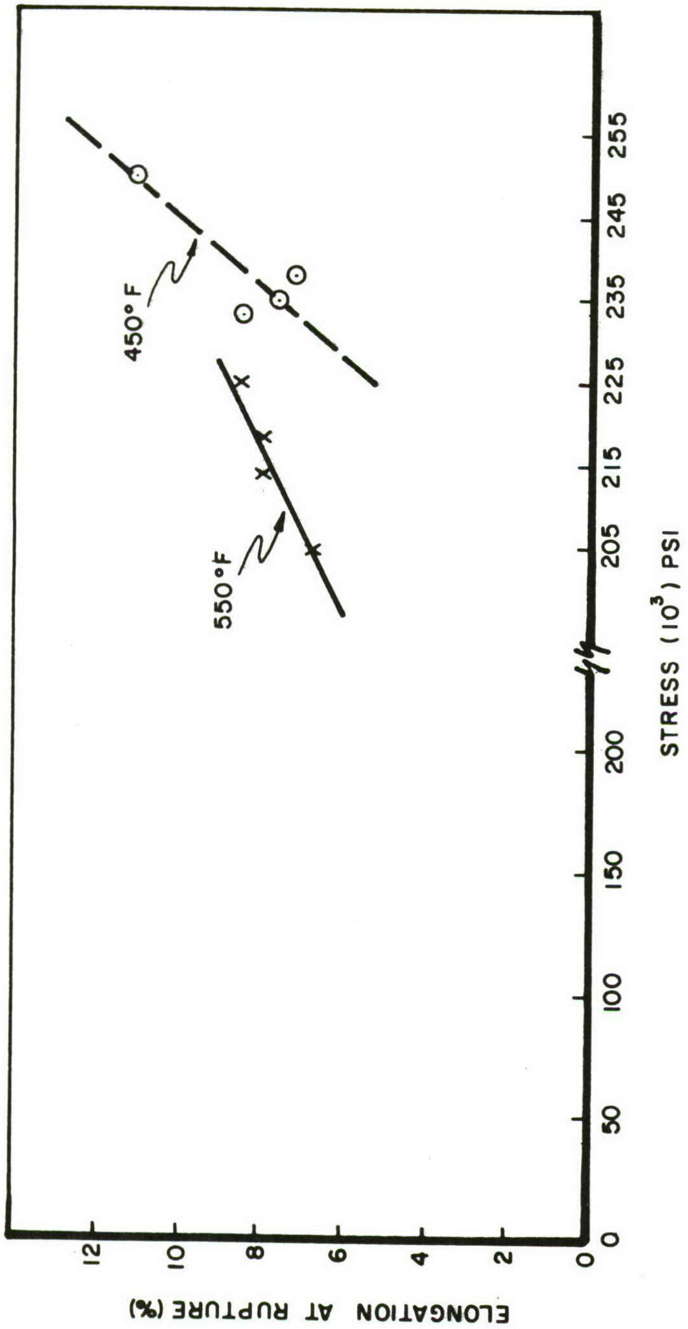

Figure 13. Final Elongation of Stress Rupture Specimens